ESTCP
Cost and Performance Report

(WP-0127)

Replacement of Chromium Electroplating on Helicopter Dynamic Components Using HVOF Thermal Spray Technology

November 2009

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page	Form Approved OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
NOV 2009	**N/A**	**-**

4. TITLE AND SUBTITLE	
Replacement of Chromium Electroplating on Helicopter Dynamic Components Using HVOF Thermal Spray Technology	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program 901 North Stuart St., Suite 303 Arlington, VA 22203**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**49**	

COST & PERFORMANCE REPORT
ESTCP Project: WP-0127

TABLE OF CONTENTS

Page

1.0 EXECUTIVE SUMMARY 1
1.1 BACKGROUND 1
1.2 OBJECTIVES OF THE DEMONSTRATION 1
1.3 REGULATORY DRIVERS 1
1.4 DEMONSTRATION RESULTS: 2
1.5 STAKEHOLDER/END-USER ISSUES 3

2.0 TECHNOLOGY DESCRIPTION 5
2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION 5
2.2 PROCESS DESCRIPTION 6
2.3 PREVIOUS TESTING OF THE TECHNOLOGY 9
2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 9

3.0 DEMONSTRATION DESIGN 11
3.1 PERFORMANCE OBJECTIVES 11
3.2 SELECTION OF TEST FACILITY 12
3.3 TEST FACILITY HISTORY/CHARACTERISTICS 12
3.4 PHYSICAL SETUP AND OPERATION 13
3.5 SAMPLING/MONITORING PROCEDURES 13
3.6 ANALYTICAL METHODS 13
3.6.1 Specimen Production 13
3.6.2 Fatigue 14
3.6.3 Fretting Fatigue 15
3.6.4 SO_2 Salt Fog Corrosion (ASTM G85-98 Annex 4) 15

4.0 PERFORMANCE ASSESSMENT 17
4.1 PERFORMANCE CRITERIA 17
4.2 PERFORMANCE DATA 17
4.2.1 Materials Testing—Fatigue 17
4.2.2 Materials Testing—Fretting Fatigue 18
4.2.3 Materials Testing—Corrosion 19
4.2.4 Component Testing—Rig Test 19
4.2.5 Qualification and Lead-the-Fleet Testing 21
4.3 DATA EVALUATION 21

5.0 COST ASSESSMENT 23
5.1 COST REPORTING 23
5.1.1 Data Provided by NADEP Cherry Point for Hard Chrome 24

TABLE OF CONTENTS (continued)

Page

5.1.1.1 Assumptions for Hard Chrome 25
5.1.1.2 Capital Costs 25
5.1.1.3 Operating Costs 25
5.1.2 Data Provided by NADEP Cherry Point and the Equipment Vendor for HVOF 26
5.1.2.1 Assumptions 26
5.1.2.2 Capital Costs 27
5.1.2.3 Operating Costs 28
5.2 COST ANALYSIS 29
5.3 COST COMPARISON 30

6.0 IMPLEMENTATION ISSUES 33
6.1 COST OBSERVATIONS 33
6.2 PERFORMANCE OBSERVATIONS 33
6.3 SCALE-UP ISSUES 33
6.4 LESSONS LEARNED 34
6.5 END-USER/OEM ISSUES 34
6.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE 35

7.0 REFERENCES 37

APPENDIX A POINTS OF CONTACT A-1

LIST OF FIGURES

Page

Figure 1. Schematic of HVOF gun and process (Sulzer Metco DiamondJet). 5
Figure 2. HVOF spray of test specimens at FRC-E. 6
Figure 3. Air handler and dust filter installation at FRC-E. 7
Figure 4. Interior of thermal spray booth at FRC-E 13
Figure 5. Smooth fatigue specimen—¼-inch diameter. 14
Figure 6. Principle of fretting fatigue system design 15
Figure 7. Fatigue of shot peened 7075 T73 Al, HVOF and EHC coatings, R=0.1, in air and room. 18
Figure 8. Fretting fatigue of 7075-T73 Al versus 52100 steel. Coatings - EHC and HVOF WC-Co. 19
Figure 9. H-46 generator gear 21
Figure 10. Hard chrome process flow at FRC-E, Cherry Point. 23
Figure 11. HVOF process flow at FRC-E, Cherry Point.. 24

LIST OF TABLES

Page

Table 1. Advantages and limitations of HVOF as a chrome replacement. 9
Table 2. Corrosion ranking per ASTM B537-70. 15
Table 3. H1 helicopter components qualified for HVOF WC-Co in place of hard chrome by Bell Helicopter testing. 20
Table 4. Base Scenario: Annual operating costs for hard chrome plating process for aircraft components. 26
Table 5. Base Scenario: Annual operating costs for HVOF thermal spray process for aircraft components 28
Table 6. Scenario 1: Annual operating costs for HVOF thermal spray process for dynamic components 28
Table 7. Annual operating costs for HVOF thermal spray process, assuming improved service life..29
Table 8. Base Scenario: Results of financial evaluation..29
Table 9. Scenario 1: Results of financial evaluation...30
Table 10. Case 1: Results of financial evaluation for increased service life of HVOF coating..30
Table 11. Case 2: Results of financial evaluation for PEL of 1.0 µg m^{-3} 30

ACRONYMS AND ABBREVIATIONS

AMS	Aerospace Materials Specification
ANSI	American National Standards Institute
ASETS	Advanced Surface Engineering Technologies for a Sustainable Defense
ASTM	American Society for Testing and Materials
BAC	Boeing Aircraft Corporation
BMS	Boeing Materials Specification
CBA	cost/benefit analysis
cermet	ceramic/metal
CFR	Code of Federal Regulations
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
ECAM	Environmental Cost Analysis Methodology
EHC	electrolytic hard chrome
EPA	Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-to-Know Act
ESTCP	Environmental Security Technology Certification Program
FRC-E	Fleet Readiness Center-East (formerly NADEP Cherry Point)
Ftu	ultimate tensile stress
GEAE	General Electric Aircraft Engines
GTE	Gas turbine engine
HCAT	Hard Chrome Alternatives Team
HDC	helicopter dynamic component
HEPA	high-efficiency particulate arresting
hex-Cr	hexavalent chromium
HVOF	high-velocity oxygen-fuel
IARC	International Agency for Research on Cancer
IAW	in accordance with
ID	internal diameter
JTP	Joint Test Protocol
ksi	thousands of pounds per square inch
MILSTD	Military Standard
MTBF	mean time between failure

ACRONYMS AND ABBREVIATIONS (continued)

NADEP-CP	Naval Air Depot Cherry Point
NAVAIR	Naval Air Systems Command
NPV	net present value
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PPE	personal protective equipment
PVD	physical vapor deposition
QC	quality control
RCRA	Resource Conservation and Recovery Act
SAE	Society for Automotive Engineers
S-N	stress vs number of cycles (fatigue curve)
T400	Tribaloy 400
TRI	toxic release inventory
TWA	time-weighted average
UAV	unmanned aerial vehicle
UTRC	United Technologies Research Center

ACKNOWLEDGEMENTS

The financial and programmatic support of the Environmental Security Technology Certification Program, under the direction of Dr. Jeffrey Marqusee, Director, and Mr. Charles Pellerin, formerly Manager of the Weapons Systems and Platforms Focus Area, is gratefully acknowledged.

The following individuals made substantial contributions to the execution of the project and preparation of this report:

Mr. Robert Kestler, FRC-E
Mr. Aaron Nardi, UTRC
Mr. Greg Haataja, Bell Helicopter
Mr. Robert Guillemette and Mr. Robert Luchenta, Sikorsky Aircraft Corp.
Mr. Robert Mason and Ms. Anne Kaltenhauser, Concurrent Technologies Corporation
Mr. Phil Bretz, Metcut Research Inc.
Mr. Andrew Schwartz, NAVAIR

Principal Investigators: Bruce D. Sartwell
Naval Research Laboratory

Keith O. Legg
Rowan Technology Group

Technical material contained in this report has been approved for public release.

This page left blank intentionally.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Electrolytic hard chrome (EHC) plating is a technique that has been in commercial production for over 50 years. It is a critical process that is used both for applying hard coatings to a variety of aircraft components in manufacturing operations and for general rebuild of worn or corroded components that have been removed from aircraft during overhaul. Chromium plating baths contain chromic acid, in which the chromium is in the hexavalent state, with hexavalent chromium (hex-Cr) being a known carcinogen. During operation, chrome plating tanks emit a hex-Cr mist into the air, which must be ducted away and removed by scrubbers. Wastes generated from plating operations must be disposed of as hazardous waste, and plating operations must abide by U.S. Environmental Protection Agency (EPA) emissions standards and the Occupational Health and Safety Administration (OSHA) permissible exposure limit (PEL). In February 2006, OSHA reduced the PEL for worker exposure to Cr^{6+} from 52μg/m^3 of Cr^{6+} to 5μg/m^3 [1]. However, at the time of writing this PEL is still in litigation, and the PEL may be further reduced in the next few years. A Navy/industry task group [2] has concluded that the cost of compliance for all Navy operations that utilize hex-Cr (i.e., not just plating) would be in excess of $10 million if the PEL were reduced to less than 5 μg/m^3.

Previous research and development efforts [3,4] had established that high-velocity oxygen-fuel (HVOF) thermal spray coatings are the leading candidates for replacement of hard chrome. HVOF thermal spraying can be used to deposit both metal alloy and ceramic/metal (cermet) such as tungsten carbide/cobalt (WC/Co) coatings that are dense and highly adherent to the base material. They also can be applied to thicknesses in the same range as what is currently being used for chrome plating. Currently, there are HVOF thermal spray systems commercially available. Although there are a wide number of applications for these coatings, their qualification as an acceptable replacement for hard chrome plating has not been adequately demonstrated, particularly for fatigue-sensitive aircraft components. The Hard Chrome Alternatives Team (HCAT) was formed to perform the demonstration/validation for the HVOF coatings. After successfully demonstrating HVOF coatings on landing gear components, hydraulic actuators, propeller hubs and gas turbine engines (GTE) [5], this project demonstrated HVOF coatings on helicopter dynamic components (HDC).

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives were to demonstrate through materials and rig testing that the performance of HVOF WC-17Co (83wt% WC particles in a 17wt% Co matrix), WC-10Co4Cr, Tribaloy 400 (T400) and duplex T400/WC-Co coatings on HDCs is equal or superior to that of EHC coatings. Materials testing included axial fatigue, fretting fatigue, and salt-fog corrosion. Rig tests were carried out on helicopter drive system and rotor system components.

1.3 REGULATORY DRIVERS

EHC plating operations must comply with the Code of Federal Regulations (CFR) 40 Part 63 (National Emissions Standards for Hazardous Air Pollutants) and 40 CFR Part 50 (National Primary and Secondary Ambient Air Quality Standards). The workplace environment must

comply with the new OSHA PEL of 5 μg/m^3 for hex-Cr, introduced in 2006, which is an order of magnitude lower than the previous PEL.

1.4 DEMONSTRATION RESULTS:

- Fatigue: Cycles-to-failure at different stress levels were measured for fatigue specimens fabricated from 4340 steel (150-170ksi), PH3-8Mo stainless steel, carburized 9310 gear steel and 7075Al, and coated with EHC (baseline), WC-17Co, WC-10Co-4Cr, Tribaloy 400, and duplex T400/WC-Co. In all cases, the fatigue of the HVOF specimens was equal or superior to the EHC. The most significant data was for 7075Al substrates, where both WC-CoCr and duplex T400/WC-Co improved fatigue significantly over EHC. This is a great improvement on the performance seen in early HCAT measurements of fatigue of HVOF-coated Al alloys that showed significant fatigue debits. All coatings passed the acceptance criteria.
- Fretting fatigue: Fretting fatigue was tested for WC-Co on each substrate against 52100 bearing steel. In all cases the fretting fatigue performance of HVOF coating, while worse than standard fatigue, was superior to EHC. Therefore, the HVOF coatings passed the acceptance criteria.
- Corrosion: ASTM B117 salt fog exposure tests were conducted on each of the substrate/coating combinations. HVOF performance was lower than that of hard chrome, just as it is in most other cabinet corrosion testing (B117 and G85). Therefore, the HVOF coatings failed the acceptance criteria. As demonstrated in HCAT beach exposure testing as well as widespread service experience, however, actual performance of HVOF coatings is usually superior to that of hard chrome. Cabinet tests, which were developed for testing paint systems and keep the surface constantly exposed to the corrodant, are known to be very poor predictors of the actual performance of these hard coatings.
- Rig Testing: Benchtop rig testing was carried out by Bell Helicopter for H-1 drive system and rotor system components coated with HVOF WC-Co in place of EHC—rotor brake disc adapter flanges, tail rotor drive quill spacers, collective scissors and sleeve, and control rods. In all cases, the HVOF coatings met or exceeded EHC performance, qualifying HVOF WC-Co for these components.
- Cost Assessment: Cost assessment was carried out using the Environmental Cost Analysis Methodology (ECAM) model, for HDCs at Fleet Readiness Center-East (FRC-E), as well for all components at FRC-E. Improved performance was taken into account, and the costs of the lower Cr^{6+} PEL were also considered. Even without considering increased service life, cost savings for HDCs alone were predicted to have a 15-year net present value (NPV) of \$3.2 million, with a payback period of 3 years, while all components had a 15-year NPV of \$7.8 million and a payback period of 2 years. When performance improvements were included, the 15-year NPV for all components increased to \$10 million. Avoidance of the additional costs required to meet a stricter Cr^{6+} PEL of 1 μg m^{-3} were estimated to have a 15-year NPV of \$8 million. However, the PEL was subsequently set at 5 μg m^{-3}, making this an overestimate.

1.5 STAKEHOLDER/END-USER ISSUES

The use of HVOF in place of hard chrome is now in use in the fleet. The CH-53 main rotor damper now uses HVOF WC-Co on the piston, HVOF T400 on the housing internal diameter (ID), and plasma spray WC-Co on a cylinder housing land.

As a result of this testing, H-1 drive and rotor system components have been qualified with HVOF WC-Co in place of hard chrome through bench testing of coated systems at Bell Helicopter. The sleeve used on the AH-1W is already HVOF WC-Co coated by the original equipment manufacturer (OEM).

Lead-the-fleet testing of H-60 dampers using HVOF coatings is under way that, assuming it is successful, is expected to result in HVOF coating of all of these dampers in the fleet to improve their mean time between failure (MTBF).

FRC-E is currently carrying out qualification testing on a set of HVOF-coated H-46 components in order to qualify HVOF for depot use. Once completed this testing will lead to overhaul use of HVOF coatings in repair of these types of components provided the process has Naval Air Systems Command (NAVAIR) concurrence.

This page left blank intentionally.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Technology background and theory of operation: HVOF is a standard commercial thermal spray process in which a powder of the material to be sprayed is injected into a supersonic flame of a fuel (usually hydrogen or kerosene), as illustrated in Figure 1. The powder particles are accelerated to high speed and soften in the flame, forming a dense, well-adhered coating on the substrate. The coating material is usually a metal or alloy (such as Tribaloy), or a cermet (such as cobalt-cemented tungsten carbide, WC-Co). The technology is used to deposit coatings about 0.003-inch thick on OEM parts and to rebuild worn components by depositing layers up to 0.015-inch thick.

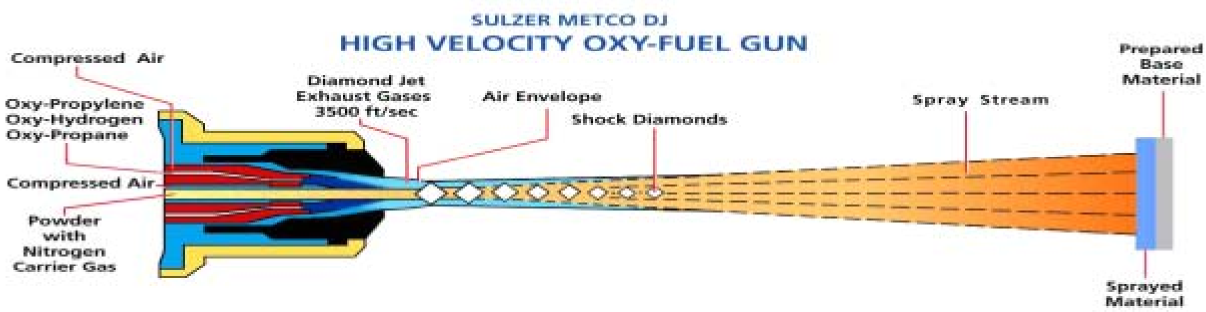

Figure 1. Schematic of HVOF gun and process (Sulzer Metco DiamondJet).

Applicability: The primary thermal spray processes are Flame Spray, Plasma Spray, Arc Spray, HVOF, and the recently-developed cold spray. The original high velocity spray technology was the detonation gun (D-gun) developed by Union Carbide (later Praxair). The quality of the wear and erosion-resistant spray coatings produced by this method was much better than the lower speed methods, and continuous flame HVOF was developed as a competitive response.

The original applications for HVOF were wear components in GTEs, such as shafts and bearing journals. As the availability and use of the technology grew, it began to be applied to a wide range of other types of coatings and applications, including a variety of aircraft components such as flap and slat tracks, landing gear and hydraulics for commercial aircraft. All new design landing gear made in Canada (where most of the world's commercial landing gear are made) are now specified for HVOF WC-CoCr in place of hard chrome plate. It is also specified for the F35 and some unmanned aerial vehicles (UAV). It is now being used in many applications outside the aircraft industry, such as industrial rolls and vehicle hydraulics. The original aircraft wear applications, primarily used by Boeing, were for otherwise-intractable spot problems that neither the original alloy nor chrome plate could solve.

The technology can be used to spray a wide variety of alloys and cermets, such as tungsten and chrome carbides in Co or CoCr alloy metal matrices. It is not used for high temperature materials

such as oxides, most of which cannot be melted in the flame. The areas to be coated must be accessible to the gun—i.e., they must be line-of-sight.

Material to be replaced: HVOF coatings are used to replace electroplated EHC, for which carbide cermets and high temperature oxidation-resistant Tribaloys are typically used. The combination of HVOF Tribaloy or nickel-aluminide with an overlayer carbide is also used to replace the combination sulfamate Ni/hard chrome. HVOF coatings are also used to replace some hard Ni and electroless Ni coatings on such components as flap tracks and propeller hubs.

2.2 PROCESS DESCRIPTION

Figure 2. HVOF spray of test specimens at FRC-E.

Installation and operation: The HVOF gun can be handheld and used in an open-fronted booth. However, the supersonic gas stream is extremely loud and requires that the operator use very good ear protection. For this reason the unit is usually installed on a six-axis robot arm in a soundproof booth, programmed and operated remotely. Most depots already use this type of booth for their existing plasma spray operations. Since the method is frequently used for cylindrical items, the most common arrangement is to rotate the component on a horizontal rotating table and move the gun up and down the axis. This is illustrated in Figure 2, which shows the HVOF spraying of a landing gear inner cylinder. A similar setup would be used for the spraying of cylindrical-shaped propeller hub components such as a lever sleeve.

Facility design: The installation requires:

- *A soundproof booth*. Booths are typically 15 ft square, with a separate operator control room, an observation window, and a high-volume air handling system drawing air and dust out of the booth through a louvered opening.
- *Gun and control panel*. The gun burns the fuel and oxygen inside its combustion chamber and injects the powder axially into the flame. The gas exits the gun at supersonic speed, while the particles are accelerated to high velocity but usually remain subsonic. The control panel controls the gas flows, cooling water, etc.
- *Powder feeder*. Powder is typically about 60 μm in diameter and is held in a powder feeder, which meters the powder to the gun at a steady rate, carried on a gas stream. Two powder feeders are commonly used to permit changeover from one coating to another without interrupting the spraying.
- *6-axis industrial robot and controller*. Most installations use an industrial robot to manipulate the gun and ensure even spraying. The robot is often suspended from above to leave the maximum possible floor space for large items.

- *Supply of oxygen*. This is frequently a bulk storage container outside the building. Alternatively, bottled gas can be used but, because of the high usage rate of up to 2000 standard cubic feet per hour (see Table 1), even a standard 12-bottle setup lasts only a few hours in production.
- *Supply of fuel gas or kerosene (bottled or bulk)*. Hydrogen is the most common fuel, supplied in bulk or in bottles. Praxair JP guns use kerosene, which is significantly cheaper and safer, and is often used for larger components because of its higher heat output and deposition rate.
- *Dust extractor and bag-house filter system*. The air extracted from the booth is laden with overspray—particles that have failed to stick to the surface (often 20-50% of the total sprayed). The air is blown into a standard bag house, often located outside the building, where the dust is removed (see Figure 3).

Figure 3. Air handler and dust filter installation at FRC-E.

- *Dry, oil-free compressed air for cooling the component and gun*. Air cooling prevents the components being overheated (temperatures must be kept below about 400°F for most high strength steels).
- *Water cooling for gun*. Not all guns are water cooled, but most are.

The facility must be capable of supplying the material pressures and flows. Standard commercial equipment currently in service already meets these requirements. Equipment vendors are able to supply turnkey systems.

Performance: HVOF guns deliver about 4-5 kg per hour of powder, of which 65% typically enters the coating, for a coating rate of about 3 kg/hour. For a common 0.010-inch WC-Co rebuild coating (which will be sprayed to a thickness of 0.013-0.015 inch), an HVOF gun can deposit about 900 in^2/hr. Thus, for example, it is possible to coat a 24-inch-long, 4-inch diameter cylinder in about 30 minutes, compared with about 15 hours for chrome plating.

Specifications: The following specifications and standards apply to HVOF coatings:

- Boeing Aircraft Corporation (BAC) 5851 thermal spray specification, supported by Boeing Materials Specification (BMS) 10-67G powder specification, is a frequently-quoted standard.
- Society for Automotive Engineers (SAE) Aerospace Materials Specifications (AMS):

- AMS 2447 was developed with the assistance of the HCAT team and issued by SAE in 1998. It is now a widely used standard in the aerospace industry.
- AMS 2448, issued in 2003, is a specification for HVOF spraying of high strength steel.
- AMS 2449 is the standard for grinding of HVOF coatings.
- AMS 7881 and AMS 7882 are powder specifications that support AMS 2448.

Training: Just as plating shops typically have several personnel who handle masking, racking, demasking, etc., it is common for HVOF shops to have three or four technicians dedicated to masking and spraying. HVOF training is essential and is usually provided by equipment vendors such as Praxair and Sulzer Metco. Training is also available through the Thermal Spray Society as well as individual consultants. Since thermal spray is a more complex technology than electroplating, plating line personnel cannot be transferred successfully to an HVOF shop without extensive retraining.

Health and safety: The process does not produce toxic air emissions or toxic wastes. Co powder is an International Agency for Research on Cancer (IARC) Group 2B material, which means that "The agent (mixture) is possibly carcinogenic to humans," whereas Cr^{6+} is an IARC Group 1 material, "known to be carcinogenic to humans". However, while the OSHA PEL for Co (8-hr time-weighted average [TWA]) of 0.1 mg(Co)/m^3, is lower than the 1 mg(Cr)/m^3 for metallic chrome, the PEL for Cr^{6+} is 0.005 mg/m^3, and the LD50 toxicity of Co is a factor of 200 lower than Cr. Unlike chrome plating, the Co is not emitted into the air. Excess Co-containing powder is drawn from the spray booth and captured in the bag house. Nevertheless personnel should wear a dust respirator when handling the powder, working in the booth, or grinding the coating since there has been a documented instance of pulmonary fibrosis ("hard metal disease") associated with early detonation gun thermal spray of WC-Co [6] by workers with inadequate personal protective equipment (PPE). While the powders are usually about 60 μm in diameter, they can break apart on impact, producing 10 μm or smaller particles. The American Welding Society recommends the use of a respirator complying with American National Standards Institute (ANSI) Z88.2.

Ease of operation: Since in commercial systems the entire system is programmable, including the gun control and robot, it is generally easy and reproducible to operate. The operator must create masking (usually shim stock shadow masks) and must develop the correct spray parameters and gun motions. While vendors supply standard operating conditions for different materials, these may have to be optimized experimentally for new materials and powders, and must be adjusted for different components to ensure proper coating speed and gun traverse rate. Small diameter components, for example, must be rotated faster than large ones to maintain the same deposition rate and coating structure. In this respect operating an HVOF system is considerably more complex than electroplating.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Prior to the HCAT program, HVOF technology had been successfully used by Boeing for a number of years for their commercial aircraft and by General Electric Aircraft Engines (GEAE) for GTEs. In the period 1993-1996, Keith Legg, Bruce Sartwell, GEAE, Cummins Diesel and Corpus Christi Army Depot carried out an evaluation of chrome alternatives under a project sponsored by the Defense Advanced Research Projects Agency (DARPA). The program evaluated HVOF, physical vapor deposition (PVD), and laser cladding and concluded that HVOF was the best overall alternative for use in depots and most OEM aircraft applications [4]. At the beginning of the HCAT program, Lufthansa successfully completed flight tests of HVOF coatings on commercial landing gear, and Delta began to carry out similar flight tests.

Prior to this project on HDCs, the HCAT had successfully validated HVOF on landing gear, hydraulic actuators, GTE components, and propeller hubs.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Replacing hard chrome plating is a great deal more complex than simply putting down a hard coating. The alternative must not only work technically but must fit with the entire life cycle of use and maintenance, and must be a reasonable, mature technology for depot use. The advantages and limitations of HVOF are summarized in Table 1.

Table 1. Advantages and limitations of HVOF as a chrome replacement.

ADVANTAGES/STRENGTHS	DISADVANTAGES/LIMITATIONS
Technical:	
Higher hardness, better wear resistance, longer overhaul cycle, less frequent replacement	Brittle, low strain-to-failure—can spall at high load. Issued primarily for carrier-based aircraft landing gear
Better fatigue, corrosion, embrittlement	Line-of-sight, cannot coat IDs
Material can be adjusted to match service requirements	More complex than electroplating. Requires careful QC*
Depot and OEM fit:	
Most depots already have thermal spray expertise and equipment	WC-Co requires diamond grinding wheel. Only HVOF alloys can be plunge ground.
Can coat large areas quickly	
Can be chemically stripped	
Many commercial vendors	
Environmental:	
No air emissions, no high volume rinse water	Co dust toxicity

*QC = quality control

This page left blank intentionally.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The performance objectives were established as a combination of materials testing done on coupons manufactured from the same base materials from which HDCs are fabricated and actual component rig testing on HVOF-coated H1 and H46 components. The materials testing requirements were established by the stakeholder team, beginning with a meeting in January 2000, and a Joint Test Protocol (JTP) was implemented starting in June 2006, after the completion of other HVOF projects.

The following materials were tested:

- Substrates: 4340 (150-170 thousands of pounds per square inch [ksi]), PH13-8Mo, carburized 9310, 7075Al
- Coatings: EHC baseline, WC-17Co, WC-10Co-4Cr, Tribaloy 400, duplex T400/WC-Co.

The performance objectives, also called acceptance criteria, were as follows:

- *Fatigue*: Cycles-to-failure at different stress levels were measured on fatigue specimens for each substrate/coating combination. These data were plotted with stress on the vertical axis and log cycles-to-failure on the horizontal axis and smooth curves were fit to the data points (designated S-N curves). If the curves for the HVOF coatings fell on or above those for the hard chrome (equal or better cycles-to-failure), then the HVOF coatings were considered to have passed the acceptance criteria. The HVOF materials met the acceptance criteria, even for aluminum alloys for which previous data had shown a debit compared with EHC.
- *Fretting fatigue*: Fretting fatigue was tested in equipment at United Technologies Research Center (UTRC) according to a UTRC test protocol. Rectangular cross section specimens were tested in axial fatigue while 52100 fretting pads contacted two opposite surfaces, at 30 ksi stress and a ±50 μm slip amplitude. As with standard fatigue, S-N curves were plotted and equal or better fatigue was classed as passing the acceptance criteria. All HVOF coatings passed the acceptance criteria.
- *Corrosion*: American Society for Testing and Materials (ASTM) SO_2 salt fog testing was carried out in accordance with (IAW) G85-98, Annex A4 on the various substrate/coating pairs. Appearance rankings and protection rankings were measured IAW ASTM B737-70. As with most other cabinet corrosion testing, the materials failed to meet the acceptance criteria. Previous experience with HVOF-coated components is that they perform better than EHC in service and in beach exposure testing, even though they show worse performance in cabinet testing.

- *Rig testing*: Bell Helicopter tested a series of drive system and rotor system components in separate drive system and rotor system tests, using systems set up on the benchtop. Test conditions were chosen to simulate service conditions, including fluid contamination with abrasive Arizona road dust.
- *Lead-the-fleet testing*: Several different gears were coated with WC-17Co at FRC-E and were still undergoing lead-the-fleet testing at time of writing.

3.2 SELECTION OF TEST FACILITY

FRC-E, Cherry Point (previously called NADEP-CP) is the Navy Center of Excellence for Vertical Left, where Navy helicopters systems are overhauled. FRC-E is equipped with HVOF spray booths, installed in the course of the depot's work on the HCAT program.

3.3 TEST FACILITY HISTORY/CHARACTERISTICS

The lead depot in this project was FRC-E, located in Cherry Point, North Carolina, which has been in existence since the early 1940s. It employs 4100 people and covers 124 acres, with more than 100 buildings, which provide roughly 1.5 million sq ft of space. The depot is the Navy's center of excellence for rotary wing aircraft and provides engineering and logistics support for all Navy helicopters. It performs major airframe modifications and repair for a wide variety of Department of Defense (DoD) aircraft including:

- AV-8B Harrier, the vertical takeoff and landing tactical attack jet flown by the Marines
- The medium-lift transport H46 Sea Knight helicopter
- The H-53D Sea Stallion and H53E Super Stallion helicopter
- The Air Force MH-53J helicopter.

The depot also repairs a number of engines including the T58 used on the H-46, the T400 used on the UH-1 helicopter, the F402 used on the AV-8B, and the T64 used on the CH-53.

Hard chrome plating is used extensively at FRC-E in all of the above repair operations and several hard chrome plating tanks of differing sizes are maintained for reworking components such as helicopter landing gear, rotor hubs, transmission gears, and engine housings. Additional operations support hard chrome plating, including stripping, cleaning, grit blasting, oven baking, and inspection. The entire plating process is performed IAW Military Standard (MILSTD) 1501 supported by QQ-C-320.

3.4 PHYSICAL SETUP AND OPERATION

FRC-E has three HVOF thermal spray booths, all of which are permitted and equipped with high-efficiency particulate arresting (HEPA) filters. Figure 4 shows one of these booths containing a spray gun, powder feeder, and three-axis robot. In the figure, the robot is on the left and the component mounting fixture on the right. In the background is the air handling system that captures any overspray powder. All of these systems are configured for processing components and no upgrades are required to place them into full production for HDCs.

Figure 4. Interior of thermal spray booth at FRC-E.

3.5 SAMPLING/MONITORING PROCEDURES

As in all coating methods, the properties and performance of the coating depends on both the coating material and the deposition conditions. Optimal coating properties can therefore be obtained only when the critical deposition parameters are in the proper range. In chrome plating, the coating properties are primarily governed by solution chemistry, temperature, and current density. HVOF spraying is more complex to optimize since there are many more variables in the deposition process. For this reason, HVOF coatings were optimized in prior HCAT projects by a Design of Experiment approach, which permits optimum conditions to be identified from a limited set of test runs, obviating the need for a full test matrix that would entail many hundreds of deposition tests.

Test methods are summarized in Section 3.1.

3.6 ANALYTICAL METHODS

The materials testing requirements and acceptance criteria were delineated in the JTP [7] and will only be summarized here.

3.6.1 Specimen Production

Specimen preparation: Shot peen to AMS 2432 under computer control to 100% surface coverage using 8-10A, S110, wrought steel shot. Carburized 9310 steel was not shot peened. EHC specimens were grit blasted with #13 glass bead IAW AMS-QQ-C-320; HVOF specimens were grit blasted with 54-60 mesh aluminum oxide IAW MIL-STD-1504.

Coating: EHC plating was done IAW MIL-STD-1501D (Class 2, Type II), supported by AMSQQ-C-320. HVOF coatings were sprayed at Hitemco with a Sulzer Metco Diamond Jet 2600 hybrid spray gun with hydrogen fuel IAW Boeing Specification BAC 5851, Class 2. Coatings/powders were as follows:

- WC-10Co4Cr/(SM 5847, SC-1015)
- WC-17Co/(D2005, SC-1017)
- Tribaloy T-400/(D3002, SC-1630).

Internal coating stress was Almen 4-12 compressive, depending on the coating material. Coating thicknesses were 0.003-0.004 inch and 0.010-0.012 inch, with duplex T400/WC-Co having layer thicknesses of 0.007-0.009 inch/0.003-0.004 inch (i.e., a thin carbide over a thick Tribaloy, an analog of sulfamate Ni/EHC. Surface finishes were 12-16 microinches for EHC, 8-10 microinches for the carbides and 10-14 microinches for T400, except where a 2-4 microinches superfinish was specified.

3.6.2 Fatigue

Load-controlled constant-amplitude axial fatigue testing was conducted IAW ASTM E466-96, using smooth bar specimen geometry shown in Figure 5. Data were taken with 10 points per curve at loads from 85% of ultimate tensile stress (Ftu) to loads low enough to give failure at about 106 cycles (runout defined as 10^7 cycles). Standard S-N curves were generated in laboratory air using an R ratio of 0.1, by plotting cyclic stress versus log cycles to failure. A least squares straight line fit was plotted through the EHC data for each coating thickness. HVOF data falling statistically on or above the baseline was considered as passing the acceptance criteria.

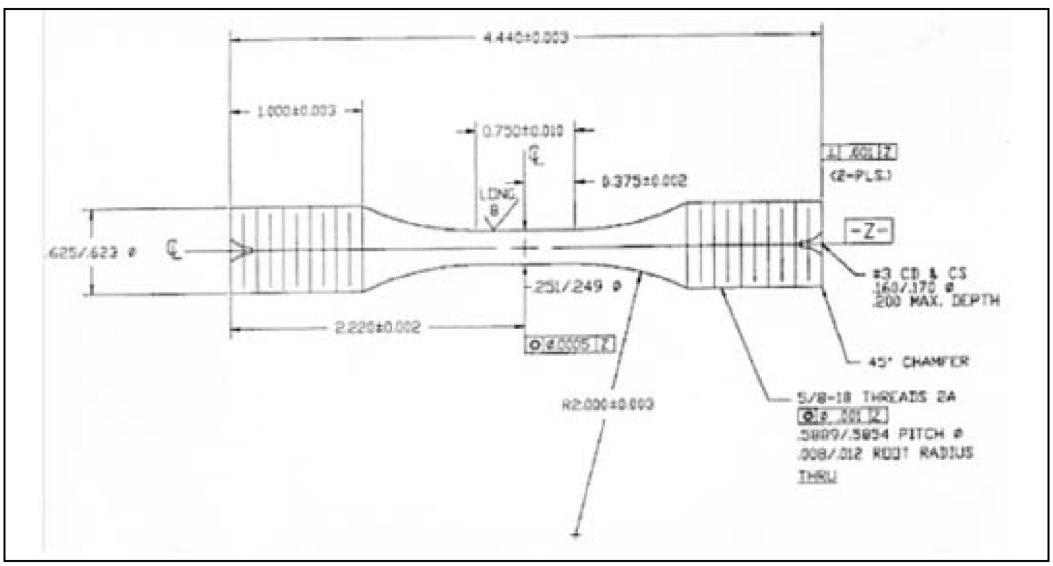

Figure 5. Smooth fatigue specimen—¼-inch diameter.

3.6.3 Fretting Fatigue

Fretting fatigue was carried out at UTRC using a standard method of their design (see Figure 6). A rectangular cross section specimen was run in axial fatigue, while 52100 steel fretting pads bore on opposite sides with a fretting contact stress of 30 ksi and a slip amplitude of ±50 μm. Coating thicknesses were 0.010-0.012 inch, with a ground surface finish of 12-16 microinches for EHC and 4-6 microinches for HVOF WC-Co (i.e., typical component finishes). Cyclic stresses were chosen to create an S-N curve from about 10_3 to 10_6 cycles, with 3-6 points per curve. Acceptance criteria were the same as for standard fatigue.

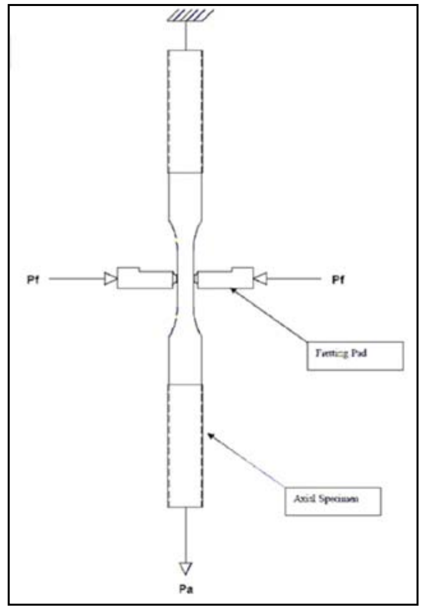

Figure 6. Principle of fretting fatigue system design.

3.6.4 SO_2 Salt Fog Corrosion (ASTM G85-98 Annex 4)

Four-inch by 3-inch specimens were coated on one side and ground to the same finish as for fatigue (see above). The back of each specimen was masked with one piece of 4-inch-wide red plastic tape, and the edges of the specimen were dipped in red plating lacquer to ensure that only the coating itself would be exposed to the salt fog. This also prevented any galvanic effects between the coated and noncoated areas. The specimens were then placed in a salt fog cabinet equipped for SO_2 salt fog testing. The specimens were inspected at the following times: 24, 72, 120, 216, 312, 360, 408, and 504 hours. At each inspection the surfaces were photographed and the appearance ranking determined IAW ASTM B537-70. Table 2 shows the ranking determination from the percentage of the surface covered with corrosion product. At the end of the test, the surface was lightly abraded to remove loose corrosion and the protection ranking (percentage of actual corrosion) measured in the same way.

HVOF coated specimens showing a lower ranking than baseline EHC-plated specimens with the same coating thickness were deemed to have failed the test.

Table 2. Corrosion ranking per ASTM B537-70.

DEFECT AREA (%)	RANK #
0	10
>0 – 0.1	9
>0.1 – 0.25	8
>0.25 – 0.5	7
>0.5 - 1	6
>1 – 2.5	5
>2.5 – 5	4
>5 – 10	3
>10 – 25	2
>25 – 50	1
>50	0

This page left blank intentionally.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA

The performance criteria for all the materials and component testing are delineated in Section 3.1. For all materials testing, the essential criterion was that the performance of specimens coated with HVOF WC/17Co, WC/10Co4Cr, or T800 should be equivalent or superior to the performance of identical specimens coated with EHC. For fatigue in particular, it is well known that the application of EHC coatings degrades the fatigue performance of high-strength steels. The issue was therefore whether the HVOF coatings would degrade the performance to a greater or lesser extent.

4.2 PERFORMANCE DATA

Only selective data and summaries are presented here. For a more detailed discussion, refer to the Environmental Security Technology Certification Program (ESTCP) Final Report [7].

4.2.1 Materials Testing—Fatigue

In all cases the fatigue of the HVOF specimens was superior to the EHC, with the largest improvement being for carburized 9310 steel. The only case in which this was not so was WCCo on 4340, which had very limited data, and where the performance was essentially the same if an outlier was neglected in the hard chrome data, or worse if the outlier was included. The most significant data was for 7075Al substrates (see Figure 7). This data shows a significant improvement in fatigue for the duplex T400/WC-Co HVOF coating, as well as for the WC-CoCr coatings. This is a great improvement on the performance seen in early HCAT measurements of fatigue of HVOF-coated Al alloys, which showed significant fatigue debits, ascribed to the difference in modulus of the carbide coatings and Al. The data produced in this program show that it is possible to deposit even thick HVOF coatings on Al alloys with no worse fatigue debit than for EHC, which suggests that the performance is not limited by the modulus difference.

HVOF coatings passed the acceptance criteria.

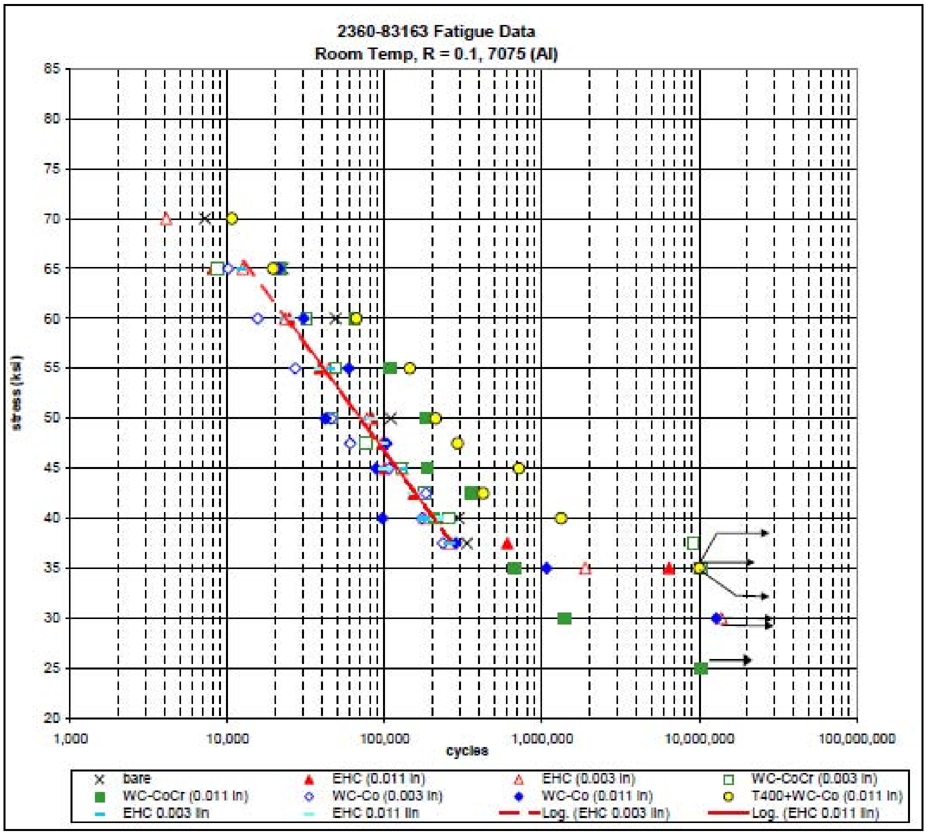

Figure 7. Fatigue of shot peened 7075 T73 Al, HVOF and EHC coatings, R=0.1 in air and room.

4.2.2 Materials Testing—Fretting Fatigue

In all cases the fretting fatigue performance of HVOF WC-Co against 52100 bearing steel was worse than standard fatigue but superior to EHC. An example of fretting fatigue performance is shown in Figure 8. The performance is lower than for conventional fatigue (Figure 7), as expected, both in terms of the cycles to failure at a specific load and in terms of the fatigue limit. In all cases the fatigue life was above what would be expected from a calculation based on a preexisting crack, ignoring the effects of shot peening.

HVOF coatings passed the acceptance criteria.

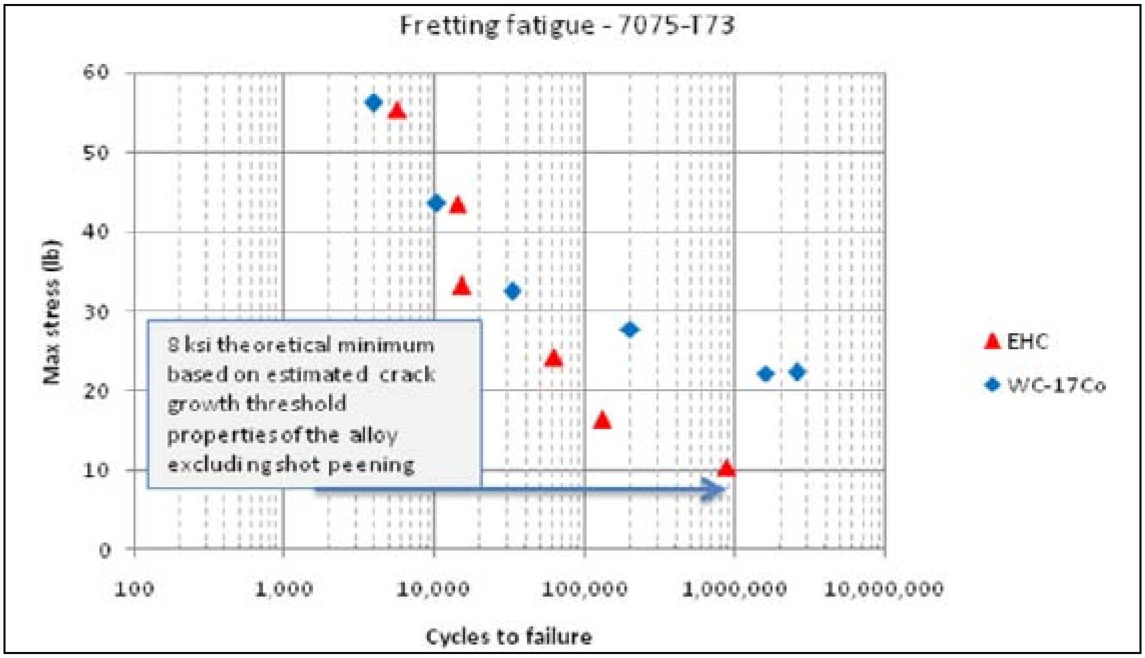

Figure 8. Fretting fatigue of 7075-T73 Al versus 52100 steel. Coatings - EHC and HVOF WC-Co.

4.2.3 Materials Testing—Corrosion

HVOF performance was lower than hard chrome, just as it is in most other cabinet corrosion testing (B117 and G85). As demonstrated in HCAT beach exposure testing as well as widespread service experience, however, actual performance of HVOF coatings is usually superior to that of hard chrome.

HVOF coatings failed the acceptance criteria, as expected for this type of test.

4.2.4 Component Testing—Rig Test

Drive System and Rotor System components for the H-1 helicopter were HVOF-coated per Bell Process Spec BPS 4463 at Southwest United and tested at Bell Helicopter in full-scale bench-top rig tests. These components are shown in Table 3.

Table 3. H1 helicopter components qualified for HVOF WC-Co in place of hard chrome by Bell Helicopter testing.

PART NUMBER	NOMENCLATURE	USED ON	BASE MATERIAL	CONTACTING SURFACE	PURPOSE OF COATING
Drive System Components					
205-040-303-001	Flange, adapter rotor brake disc	UH-1	4340 alloy steel	Oil seal, 450071-H	Hard riding surface for seal, corrosion resistance
209-040-177-101	Flange, adapter rotor brake disc	AH-1	4140 alloy steel	Oil seal, 450071-H	
212-040-156-001-101	Spacer, tail rotor drive quill	UH-1 AH-1	4140 alloy steel	Oil Seal, 41858-H60	
204-040-313-001	Spacer, tail rotor drive quill	UH-1	4140 alloy steel	Oil Seal, 41858-H60	
Rotor System Components					
214-010-411-003	Sleeve, collective scissors and sleeve, main rotor controls	UH-1H	4340 alloy steel	Woven teflon fabric on aluminum	Wear resistance
214-010-716-001	Control rod, tail rotor	AH-1T	4130 alloy steel	Nylatron GS seal	
214-010-855-105	Control rod, tail rotor	AH-1W, AH-1T	15-5 PH, CRES	Nylatron GS seal	

Drive System: The Drive System components were tested with HVOF WC-Co coatings as a qualification test of the HVOF coating. The chrome plate on these components is only 0.0005-inch thick, thinner than HVOF coatings can be made. Thus it can be replaced only if HVOF coatings can be used without compromising fit, form, and function.

The test was a 100-hour test with brake stops that induced thermal cycling to 270°F. The testing was designed to demonstrate that the HVOF coating does not affect the sealing at the seal lip/flange interface and does not increase the seal lip wear rate.

There was no appreciable wear of the WC-Co, and the test was successful in qualifying the HVOF applied tungsten carbide coating, when applied per BPS 4463, as a replacement for chromium plate for all components listed in Table 3.

Rotor System: The rotor system components were standard stock components coated with HVOF WC-Co and tested in comparison with stock chrome plated components, using stock bearings and guides. EHC on these components is 0.002-inch thick, and can be directly replaced with HVOF. The test consisted of 50,000 cycles of full stroke testing followed by 5000 cycles of testing with the addition of Arizona road dust.

There was no indication of wear or damage to the HVOF-coated area of the modified rod tested or on the chromium plated area of the baseline rod. In the comparison test between the HVOF tungsten carbide coated rod and the chromium plated baseline rod, the performance was the same, and no differences were noted as evidenced by visual and microscopic inspection of the coated surface.

The test was successful in qualifying the HVOF applied tungsten carbide coating, when applied per BPS 4463, as a replacement for chromium plate for all components listed in Table 3.

4.2.5 Qualification and Lead-the-Fleet Testing

A fleet-wide change has been implemented, with CH-53 main rotor dampers now being coated with HVOF coatings in place of hard chrome.

At the time of writing, FRC-E is carrying out lead-the-fleet testing of modified H-60 main rotor dampers to eliminate frequent failures due to abrasive particle damage to the current system. These components are modified by the use of WC-Co on the piston, HVOF T400 on the outer cylinder ID, and plasma spray WC-Co on a cylinder land. They also include a stainless steel bushing and modified seal design. Testing is currently under way, and all components have passed the MTBF of the current system (650 hr), with the aim of reaching 1500 hours.

At the time of writing, FRC – East (Cherry Point) is carrying out a 200-hour endurance test for qualification on a number of H-46 helicopter components coated with HVOF WC-Co:

- Input gear
- Generator gear
- Utility pump drive gear
- Aft input gear
- Aft sun gear
- Planet carrier
- Collector gear.

CH-46 generator gears (Figure 9) have already been prototyped and successfully tested in a 150-hour endurance test.

Figure 9. H-46 generator gear.

4.3 DATA EVALUATION

Performance: In common with most other wear applications, HVOF performs better than EHC in most respects, including wear and fatigue. Also in common with other cabinet corrosion tests, HVOF does not perform as well as EHC. However, it has been found in prior test programs that HVOF WC-Co coatings generally perform better than EHC in both beach exposure and in service. Cabinet corrosion tests, which were designed for testing paint systems, are not valid tests for hard coatings of this type since they do not reflect service performance.

This test protocol was the first time that HVOF coatings have been tested by HCAT in fretting fatigue. Because HVOF carbides provide better wear and fatigue, it is not surprising that they also give better fretting fatigue protection. This program also demonstrated that HVOF carbide can be used on aluminum alloys without causing an excessive fatigue debit.

Personnel and training: Personnel training requirements for HVOF spraying are more extensive than for hard chrome electroplating. The method requires a trained technician able to set up the equipment for the correct coating conditions, including shielding and temperature

control. Training is available from a variety of sources, including equipment manufacturers, the Thermal Spray Society, and a number of private consultants.

Health and safety: HVOF spraying does not create Cr^{6+} emissions. However, spray particle sizes are generally in the region of 25-50 microns, and a proportion of the material sprayed does not adhere to the substrate but bounces off and often breaks into fines. Co is not a known carcinogen, as Cr^{6+} is, but it can cause eye and skin irritation. Workers are not present in the spray booth during spraying, and overspray powder is ducted away and trapped in a bag house filter (see Figure 3). Inhalation exposure to cobalt and WC-Co can lead to “hard metal” pneumoconiosis (fibrosis and scarring of the lung from occupational exposure), which has historically been seen in workers exposed in WC-Co manufacturing plants. (WC-Co is a widely used material for wear-resistant cutting and forming tools). There has been a report of a similar problem with a thermal spray worker in 1989 [6]. Therefore, workers should wear respirators when entering the spray booth or handling WC-Co powder.

Most spray systems use hydrogen fuel. This requires proper handling and leak detection as well as proper explosion-proofing of the booth.

Ease of operation: All the equipment and materials are commercially available. In most booths the equipment is computer controlled, with the spray gun mounted on a robot. Since the method is line-of-sight, it is essential that the spray pattern be properly set up. This is more complex than electroplating. On the other hand, the process is well-controlled and reproducible.

Limitations: There are two primary limitations of HVOF spray:

1. It cannot be used for non-line-of-sight areas such as deep IDs.
2. It cannot be used to deposit high quality continuous coatings thinner than about 0.002 inch.

Most HVOF coatings are specified at 0.003 inch or above after grind.

Other differences: If there are areas adjacent to the sprayed area that should not be coated, they must be masked using metallic hard masks (not tapes, such as are used in electroplating). WCCo can be ground only with a diamond wheel, and the finish must in general be smoother than EHC—typical requirements are 4-8 microinches Ra. Coatings that are too rough can cause excessive wear on counterfaces.

5.0 COST ASSESSMENT

5.1 COST REPORTING

Cost analysis was done using the ECAM methodology. Figure 10 and Figure 11 show the flow diagrams for hard chrome plating and HVOF, respectively.

Two scenarios and two cases applied to the Base Scenario were developed and analyzed for this cost/benefit analysis (CBA). The first scenario (Base Scenario) considers all aircraft components. Scenario 1 evaluates HDCs only. It should be noted that HDCs account for only 30% (37% by surface area) of total chrome electroplating at FRC-E. In an attempt to isolate these costs, a percentage of the total electroplating costs were used; labor and related costs were based on the production variance (i.e., number of parts); materials and related costs were based on the percent variance in surface area being coated. Since these costs cannot be easily separated, this method provides only a rough estimate of actual HDC plating costs.

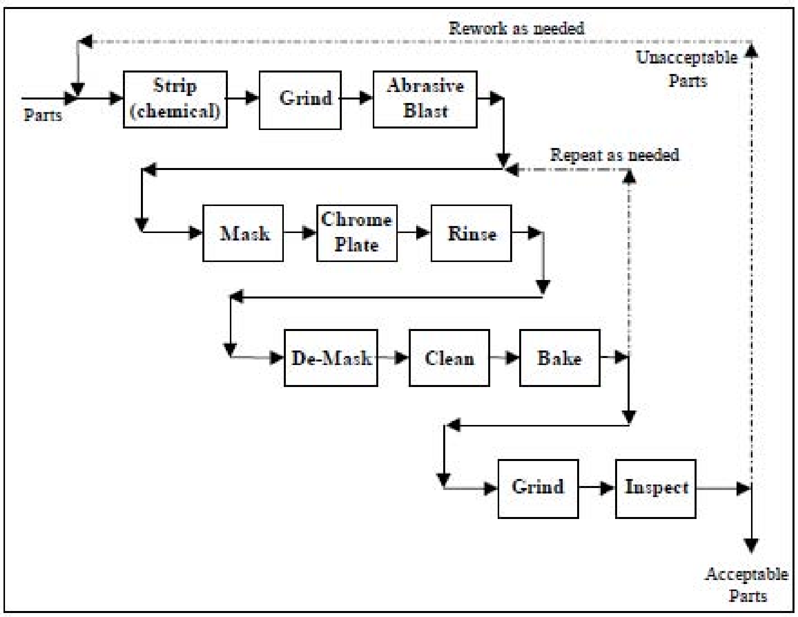

Figure 10. Hard chrome process flow at FRC-E, Cherry Point.

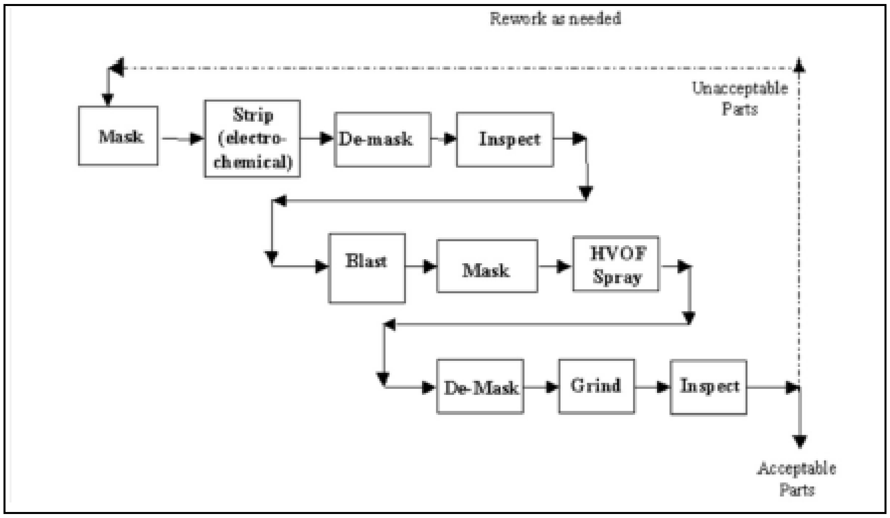

Figure 11. HVOF process flow at FRC-E, Cherry Point.

In addition, two cases were applied to the Base Scenario. Case 1 analyzed the impact of expected increased service life of the aircraft components with HVOF coating. Case 2 analyzed the impact of the proposed OSHA chromium exposure regulation. Since the CBA was completed prior to announcement of the new PEL, it assumed a PEL of 1 µg m^{-3}, whereas the actual level subsequently enacted was 5 µg m^{-3}. Thus the impact of the regulation was presumably somewhat overestimated.

A site visit was conducted on August 5-6, 2003, to collect baseline data on the hard chrome plating process at NADEP Cherry Point. The data collection form used for this purpose is provided in Appendix A of the Final Report. During the site visit or after via telephone, interviews were held with process engineers, plating operators, environmental staff, and other employees throughout the facility. The information gathered during the site visit was supplemented with additional correspondence following the visit.

5.1.1 Data Provided by NADEP Cherry Point for Hard Chrome

NADEP Cherry Point provided information on the following items, either during the site visit or during follow-up correspondence.

- Annual current usage in chrome plated department
- Annual quantities and/or costs for electroplating and stripping chemicals, maskant, and tape
- Annual cost and labor for anodes
- Annual labor required for plating and lab analysis
- Annual costs for scrubber usage
- Labor required for addressing spills and monitoring in the plating area
- The chrome plating shop, which is operated 50 weeks per year with overtime as required

- Total annual surface area chrome plated for various components
- Estimated component production was given as 10% for propeller components, 10% for actuators, 37% for dynamic components, and 35% for landing gear. Eight percent of the parts chrome plated is for components not included in this analysis; this amount is considered negligible; therefore, total plating costs given by NADEP Cherry Point were used in this analysis.
- Cost for plating waste disposal.

5.1.1.1 Assumptions for Hard Chrome

The following engineering assumptions were used in evaluating the baseline hard chrome plating process:

- NADEP Cherry Point estimated water usage costs to be negligible.
- Cost for anode disposal is minimal as lead is recycled.
- Annual cost of PPE was considered negligible.
- Cost for fixturing disposal is minimal as it falls under the Resource Conservation and Recovery Act (RCRA) scrap metal exclusion.
- Rework is estimated at 2%; however, these costs were not calculated independently but considered to be captured in the total annual operating costs.
- Total plating tank electricity usage and cost were estimated based on calculations made at other facilities.
- For Scenario 1 and for plating costs after implementation, a percentage of total plating costs was used. Labor costs were estimated based on the percentage of actual parts plated; material and related costs were estimated based on a percentage of total surface area plated.
- Costs for medical exams were estimated at $400 per exam and 4 hours of lost work.
- Labor to maintain/inspect hazardous accumulation sites was estimated at $375 per year.
- Total scrubber costs were used for both the Base Scenario and Scenario 1.

5.1.1.2 Capital Costs

All capital costs for the baseline process are considered sunk costs; therefore the Base Scenario and Scenario 1 do not include any capital expenditures.

5.1.1.3 Operating Costs

Table 4 provides a summary of annual labor, material, utility, and waste disposal costs for the baseline hard chrome plating process for all items and for HDCs only (Scenario 1). In addition to

these annual costs, periodic costs were captured: material costs of $800,000 every 3 years for scrubber mesh pads.

Table 4. Base Scenario: Annual operating costs for hard chrome plating process for aircraft components.

RESOURCE	BASE SCENARIO ANNUAL COST ($/YR)	SCENARIO 1 (HDCS ONLY) ANNUAL COST[A] ($/YR)
Labor	$1,761,500	$606,301
Materials	$5430	$1639
Utilities	$39,353	$25,842
Waste disposal	$44,303	$14,361
Environmental management costs	$21,290	$8317
Total Annual Operating Cost	**$1,871,876**	**$656,460**

5.1.2 Data Provided by NADEP Cherry Point and the Equipment Vendor for HVOF

- Cost of WC-Co material is $46.31 per pound.
- WC-Co spray rate is 10.61 pounds per hour.
- WC-Co spray weight is 0.057 lb/ft^2/mil.
- Transfer efficiency of WCCo is 36%; this includes a 10% stand-off time.
- Total surface area for the aircraft components is 658,700 square inches per year.
- Total surface area for the dynamic components is 192,621 square inches per year.
- Total fuel costs are $76 per hour of operation.
- HVOF gun barrels cost $218.
- HVOF gun barrel life is 20 hours of spray time.
- Labor for laboratory analysis.
- Equipment utility requirements.
- Equipment needs and costs.
- WCCo is deposited to 8 mil thickness.
- All operating parameters are based on Sulzer-Metco equipment specifications.

5.1.2.1 <u>Assumptions</u>

The following engineering assumptions were used in evaluating the HVOF thermal spray coating process:

- Approximately 65% of the dynamic components and 68% of all other components that are currently chrome plated will be transitioned to HVOF; the remainder of

the parts have non-line-of-sight areas that need plated and therefore cannot be transitioned to HVOF. It is assumed that the remaining percentage of the component surface area will still be plated.

- HVOF labor requirements were estimated at one full-time employee per booth.
- HVOF operators will spend approximately two-thirds of the time spraying and one-third setting up, testing, and cleaning equipment.
- HVOF equipment will operate one shift per day, 50 weeks per year.
- Cost to decommission plating tanks will equal their salvage value.
- Cost of rework is negligible.
- Stripping costs are expected to be similar for both processes; therefore, these were not captured in this analysis.
- Cost for labor and materials for shielding and fixturing is equal to cost for plating anodes and fixturing.
- The cost of goggles, respirators, and hearing protection per employee is not expected to change with implementation
- Reporting costs for spill/emergency release, toxic release inventory (TRI) and Emergency Planning and Community Right-to-Know Act (EPCRA) are not expected to change with implementation of HVOF.
- Baking ovens will not be shut down with HVOF implementation, as some baking is still needed for the electroplated parts.
- Implementation of HVOF would allow for one of the three plating tank scrubbers to be shut down; NADEP Cherry Point estimated resulting operating costs.

5.1.2.2 Capital Costs

NADEP CP has already purchased two HVOF booths that could be used for this application. However, at the request of NADEP CP, transitioning these booths for this application was not considered in this analysis, but rather capital expenditures to purchase additional booths were used. This allows for an investment payback to be calculated. For the Base Scenario, $1,200,000 in capital equipment costs was considered, and $600,000 in capital equipment costs was considered for Scenario 1. Existing air filtration and grinding equipment will be used; therefore no additional capital equipment costs were considered for these. As facility employees are presently using HVOF equipment, no additional training costs were included.

All equipment costs were expensed using straight-line depreciation over 15 years. Useful life and salvage values were estimated using Air Force Instruction 38-203 as guidance[1].

[1] HVOF equipment - Stock Class 3433, Gas Welding, Heat Cutting and Metalizing Equipment: 15-year life, 0.06760 salvage value.

5.1.2.3 <u>Operating Costs</u>

The base scenario costs for aircraft components are shown in Table 5.

Table 5. Base Scenario: Annual operating costs for HVOF thermal spray process for aircraft components (includes continued electroplating of 35% of parts).

RESOURCE	ANNUAL COST[A] ($/YR)	
	Plating	**HVOF**
Labor	$604,630	$278,265
Materials	$1555	$274,515
Utilities	$13,035	$41,504
Waste disposal	$14,485	$1280
Environmental management costs	$8548	$0
Total Annual Operating Cost by Process	$642,253	$595,564
Total Annual Operating Cost		**$1,237,817**

[a] Values are rounded to the nearest tenth

The annual operating costs for dynamic components under Scenario 1 are shown in Table 6.

Table 6. Scenario 1: Annual operating costs for HVOF thermal spray process for dynamic components (assumes 65% transition to HVOF).

RESOURCE	ANNUAL COST[A] ($/YR)	
	Plating	**HVOF**
Labor	$195,522	$141,505
Materials	$499	$80,278
Utilities	$8711	$12,137
Waste disposal	$4971	$1280
Environmental management costs	$4455	$0
Total Annual Operating Cost by Process	$214,158	$235,200
Total Annual Operating Cost		**$449,358**

[a] Values are rounded to the nearest tenth

Case 1: Increased Service Life of HVOF Coating (Declining Throughput)

The following assumptions were used to analyze the cost benefit of a scenario in which HVOF coating improves service life:

- *Years 1-5*: All aircraft components coming into the depot have chrome plating that is stripped for inspection and repair purposes. Applicable components are recoated using HVOF thermal spray at the current throughput rate of 6219 (11,000 total plating production minus the non-line-of sight parts that will continue to be plated) parts per year.
- *Years 6-10*: 50% of the components processed are chrome-plated parts, which are stripped, inspected, repaired, and recoated using HVOF thermal spray. It is assumed that the remaining 50% of the parts were previously coated using HVOF.

It is estimated that 25% of these components (12.5% of the total throughput) will be stripped, inspected/repaired, and recoated using HVOF. The remaining components (37.5% of the total throughput) will require no processing. Thus, the total number of parts processed annually will be 3887 components.

- *Years 11-15*: All aircraft components coming into the depot were previously coated using HVOF. Of these, 25% will be stripped, inspected/repaired, and recoated using HVOF thermal spray. The total number of parts processed annually will be 1555 components.

The costs for this case are summarized in Table 7.

Table 7. Annual operating costs for HVOF thermal spray process, assuming improved service life.

RESOURCE	ANNUAL COST[A] ($/YR)		
	Years 1-5	**Years 6-10**	**Years 11-15**
Labor	$882,895	$778,546x	$674,196
Materials	$276,071	$173,127	$70,184
Utilities	$54,539	$38,975	$23,411
Waste disposal	$15,765	$15,285	$14,805
Environmental management costs	$8548	$8548	$8548
Total Annual Operating Cost	**$1,237,818**	**$1,014,481**	**$791,144**

[a] Values are rounded to the nearest tenth

Case 2: Effect of a reduction in the Cr^{6+} PEL to 1 μgcm^{-3}: The additional cost was estimated to be between $41,000 and $99,000 annually if the baseline hard chrome process continues to be used. The estimate changed to $36,000 to $56,000 if HVOF was adopted, while retaining hard chrome only for components requiring non-line-of-sight coating.

5.2 COST ANALYSIS

Tables 8, 9, 10, and 11 summarize the potential cost savings for different scenarios. As is normal for cost analyses of HVOF processes, additional cost savings derive from including in the calculation the improved performance of HVOF coatings in the out years (Table 10).

Table 8. Base Scenario: Results of financial evaluation (all aircraft components).

FINANCIAL INDICATOR	5-YR	10-YR	15-YR
Net present value	$2,211,343	$5,208,631	$7,842,352
Internal rate of return	50.4%	57.1%	57.7%
Discounted payback	1.97 years		

Table 9. Scenario 1: Results of financial evaluation (helicopter dynamic components only).

FINANCIAL INDICATOR	5-YR	10-YR	15-YR
Net present value	\$839,141	\$2,110,197	\$3,232,980
Internal rate of return	36.7%	44.9%	45.9%
Discounted payback	3.02 years		

Table 10. Case 1: Results of financial evaluation for increased service life of HVOF coating (all aircraft components, declining throughput).

FINANCIAL INDICATOR	5-YR	10-YR	15-YR
Net present value	\$2,211,343	\$6,111,603	\$10,326,034
Internal rate of return	50.4%	58.8%	59.6%
Discounted payback	1.97 years		

Table 11. Case 2: Results of financial evaluation for PEL of 1.0 µg m^{-3} (mean values).

FINANCIAL INDICATOR	CONTINUOUS THROUGHPUT
15-year net present value	\$8,066,000
Internal rate of return	59.2 %
Discounted payback	1.91 years

5.3 COST COMPARISON

In comparing the costs for HVOF versus chrome plating, the largest saving is in labor cost since HVOF requires fewer personnel. Materials costs for HVOF are higher, and there is a capital cost for each new spray booth. Environmental management costs are eliminated with HVOF because the materials are not toxic and there is no contaminated wastewater. Hazardous waste is not eliminated; however, all the while, hard chrome must be stripped from existing components and disposed of as hazardous waste.

Worker PPE is required for spray operators when entering the spray booth. However, unlike chrome plating, no workers are exposed in the general shop environment. Because HVOF does not use or create Cr^{6+}, there is no danger of exceeding the Cr^{6+} PEL action level, which triggers additional paperwork and the potential for liability. Thus the risks with HVOF are lower than with chrome plating.

The effect of a substantial reduction in the Cr^{6+} PEL was estimated from a combination of costs estimated by OSHA and by FRC-E, Cherry Point. Since, at the time of the analysis, the new PEL had not been announced, it was assumed that it would be 1 µg m^{-3} 8-hr TWA with an action level of 0.5 µg m^{-3}, but the actual PEL was set at 5 µg m^{-3} 8-hr TWA, with an action level of 2.5 µg m^{-3}. Since most plating shops carry out both chrome plating and chromate conversion

coating, replacing the chrome plating but not the conversion eliminates some but not all of the additional costs for engineering controls and PPE that will be required to meet the PEL. This means that the model probably represents an overestimate of the costs of the PEL, although it is not clear how large that overestimate might be. One cost saving that is assuming greater importance at today's higher operational tempo is turnaround time. HVOF coating represents a considerable time saving since it avoids the extensive hydrogen baking that is required by multiple plating steps. Where this is a rate limiting step, HVOF will lead to more rapid turnaround and quicker return of aircraft to active duty. In addition, the better performance of HVOF coatings should result in reduced operational maintenance downtime for seals and worn components. Unfortunately, there is no accepted methodology for accounting for these cost reductions.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The major cost issue for HVOF implementation is the capital cost of additional booths, including their installation. In addition HVOF requires enhanced operator training, optimization of the process for new components if they are significantly different from ones previously sprayed, and programming of the robot for spraying components of different size and shape. However, the cost savings that devolve from its better wear, corrosion, and fatigue are the major nonenvironmental drivers for the use of HVOF for overhaul.

Not included in the cost analysis are the up-front costs of individual component qualification, where required by approval authorities, and changes to drawings, technical documents, and specifications. These costs drop as the process becomes more widely accepted. Some individual component qualifications are still likely to be needed in order to apply HVOF to additional HDCs, but qualification by similarity will bring HVOF into use on more and more components as it proves able to provide better performance without significant risk of failure.

6.2 PERFORMANCE OBSERVATIONS

The acceptance criteria are always that the performance of the replacement should be "as good as or better than" the material it replaces. In most respects, HVOF performance is superior to hard chrome although, in the drive and rotor system bench tests carried out under this program, the test conditions were sufficiently benign that there was no significant deterioration either in the baseline or the alternative. As a result of rig testing carried out in this program, HVOF WC-Co has been qualified for H-1 drive and rotor system components.

The only test in which HVOF did not meet the performance of hard chrome was the ASTM G85-98 corrosion test. However, as we have noted in Section 4.2.3, the ASTM G85-98 test was developed for paint systems and is known to have little or no relationship to the actual service performance of hard coatings. Service experience with HVOF carbide coatings on other systems such as landing gear and hydraulic actuators has shown the HVOF coatings to have corrosion performance significantly superior to hard chrome. There is no reason to expect inferior results for HDCs.

Lead-the-fleet testing is still ongoing at FRC-E. No negative issues have been found to this point.

6.3 SCALE-UP ISSUES

There are no scale-up issues.

The HVOF systems currently in operation at aerospace-qualified HVOF vendors and at the FRCs and Air Logistics Centers are full-production systems with fixturing for manipulation of various types of components and robots on which the HVOF spray guns are mounted. The original spray booth at FRC-E that was acquired using ESTCP funds has now been supplemented by additional booths acquired by the FRC to meet demand. These booths are expected to be used for

processing helicopter drive and head, propeller hub, landing gear, and other components for fixed-wing and rotary-wing aircraft.

Most OEMs purchase their HVOF services from various commercial vendors. These commercial shops already use full-scale HVOF equipment.

6.4 LESSONS LEARNED

This is the first HCAT project that has evaluated the fretting fatigue performance of HVOF coatings. As expected, HVOF coatings perform better under fretting than EHC because they are harder and less easily damaged.

Another very important finding from this work is that it is possible to use HVOF carbide coatings on aluminum alloys without causing a serious fatigue debit. In some ways this reflects the growing experience of the vendor community with the deposition and optimization of HVOF coatings, since improved fatigue was found even for a simple WC-CoCr coating that in prior HCAT work had been found to give a significant debit below hard chrome. However, it was found that much better fatigue could be obtained by the use of a duplex T400/WC-Co coating for rebuilding worn Al. This approach makes the process less dependent on the precise optimization of the carbide coating and so makes it more viable for general depot use without risk of creating a fatigue debit. Since Al is quite commonly used for helicopter landing gear components, this finding makes HVOF a more reliable tool for overhaul.

The fatigue data on carburized 9310 steel also showed that it is possible to apply HVOF coatings to carburized surfaces such as gear journals.

6.5 END-USER/OEM ISSUES

The primary test location at FRC-E is the Navy Vertical Lift Center of Excellence, which is the primary location for repair of Naval rotary wing aircraft. The project was run in close collaboration with the rotary wing OEMs, Sikorsky, Boeing Helicopter, and Bell Textron. Bench testing was carried out by Bell.

As a result of the bench testing, the tested H-1 drive and rotor system components have been qualified with HVOF WC-Co in place of hard chrome.

FRC-E is currently carrying out qualification testing on a set of H-46 components in order to qualify them for depot use. Once completed this testing will lead to overhaul use of HVOF coatings in repair of these types of components, provided the process has NAVAIR concurrence.

The use of HVOF in place of hard chrome is already in use in the CH-53 fleet. The main rotor damper now uses HVOF WC-Co on the piston, HVOF T400 on the housing ID, and plasma spray WC-Co on a cylinder housing land.

Lead-the-fleet testing of H-60 dampers using HVOF coatings is under way, and assuming it is successful it is expected to result in HVOF coating of all of these dampers in the fleet to improve their MTBF.

6.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The principal environmental and worker safety issues associated with HVOF thermal spraying are air emissions containing overspray particles and the noise of the gun itself. All the depots that use thermal spray have the appropriate spray booths, spray equipment, air handling equipment (booth exhaust systems and dust collection bag houses), fuel supplies, and air handling equipment in place as well as the appropriate air permits to cover operation of the HVOF systems.

The equipment is installed in soundproof booths, with robot and computer-controlled spray systems. Spray booths are designed to be explosion-proof, with hydrogen detectors for hydrogen-fueled systems. Operators do not enter the booth during spraying, and whenever they do enter the booth before or after a spray run, they are protected with a proper dust mask. This ensures that there is no operator exposure either to noise or to dust generated during spraying.

7.0 REFERENCES

1. "OSHA Cr^{6+} PEL final rule," Federal Register, Vol. 71, No. 39 (February 28, 2006).

2. Navy/Industry Task Group Report, "Impact of Anticipated OSHA Hexavalent Chromium Worker Exposure Standard on Navy Manufacturing and Repair Operations," October 25, 1995.

3. "High Velocity Oxy Fuel Final Results Report," Final Report issued by Science Applications International Corporation under government Contract F09603-90-D2215, Oklahoma City Air Logistics Center, Tinker Air Force Base, May 25, 1994.

4. "Hard Chrome Coatings: Advanced Technology for Waste Elimination," Final Report, October 1997. http://www.materialoptions.com/FoxSuite/orgview/filestream2.aspx?orgname=SURFACE%20ENGINEERING%20DATABASE&filename=../Storage/group\SURFACE%20ENGINEERING%20DATABASE\Hard%20Chrome%20Alternatives\Qualified%20Engineering%20Data\Reports/Final%20Report%20original%20DARPA%20project.pdf.

5. All HCAT reports can be found in the ASETS Defense database at http://db.asetsdefense.org/ (search for Alternative to: Hard Chrome Plate; Document Category: Technical Report).

6. "Pulmonary Fibrosis Associated with Occupational Exposure to Hard Metal at a Metal-Coating Plant--Connecticut, 1989", CDC MMWR January 31, 1992 / 41(04);65-67 http://www.cdc.gov/mmwR/preview/mmwrhtml/00016007.htm.

7. "Validation of HVOF Thermal Spray Coatings as Replacements for Hard Chrome Plating On Helicopter Dynamic Components", June 2005, ESTCP Project WP-0127 Final Report, November 2009, www.estcp.org http://www.materialoptions.com/FoxSuite/orgview/filestream2.aspx?orgname=SURFACE%20ENGINEERING%20DATABASE&filename=../Storage/group\SURFACE%20ENGINEERING%20DATABASE\Hard%20Chrome%20.

8. Alternatives\Qualified%20Engineering%20Data\Test%20Protocols/HVOF%20for%20Hard%20Chrome%20Replacement%20on%20Helicopter%20Dynamic%20Components%20JTP.pdf.

APPENDIX A

POINTS OF CONTACT

POINT OF CONTACT NAME	ORGANIZATION	PHONE FAX E-MAIL	ROLE
Bruce D. Sartwell	SERDP/ESTCP Program Office 901 North Stuart Street Suite 303 Arlington, VA 22203-1853	703-696-2128 703-696-2114 bruce.sartwell@osd.mil	Principal Investigator/ Program Manager, Weapons Systems and Platforms
Keith O. Legg	Rowan Technology Group 1590 South Milwaukee Avenue, Suite 205 Libertyville, IL 60048	847-680-9420 847-680-9682 klegg@rowantechnology.com	Co-Principal Investigator

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

E-mail: estcp@estcp.org
www.estcp.org